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## AWAKE: A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN

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### Abstract

The AWAKE Collaboration has been formed in order to demonstrate proton-driven plasma wakefield acceleration for the first time. This acceleration technique could lead to future colliders of high energy but of a much reduced length when compared to proposed linear accelerators. The CERN SPS proton beam in the CNGS facility will be injected into a 10 m plasma cell where the long proton bunches will be modulated into significantly shorter micro-bunches. These micro-bunches will then initiate a strong wakefield in the plasma with peak fields above 1 GV/m that will be harnessed to accelerate a bunch of electrons from about 20 MeV to the GeV scale within a few meters. The experimental program is based on detailed numerical simulations of beam and plasma interactions. The main accelerator components, the experimental area and infrastructure required as well as the plasma cell and the diagnostic equipment are discussed in detail. First protons to the experiment are expected at the end of 2016 and this will be followed by an initial three-four years experimental program. The experiment will inform future larger-scale tests of proton-driven plasma wakefield acceleration and applications to high energy colliders.

**Keywords:** Plasma, wakefields, protons, proof-of-principle, self-modulation

## 1. Introduction

Lepton linear colliders, operating at the TeV energy scale, represent one option to search for new physics and complement the results obtained from the LHC at CERN. The present RF cavities or microwave technologies allow to achieve a maximum accelerating gradient of  $\sim 100$  MV/m. The future linear colliders should then be several tens of kilometres long to achieve the TeV range. It was predicted that a plasma can sustain three orders of magnitude higher gradients than the RF cavities [1, 2] so that studies on possible “compact” plasma-based accelerators became of great interest. A plasma acts as an energy transformer which transfers the energy from a drive to a witness bunch. The maximum energy gain per particle of the accelerated beam, in a single plasma stage, is limited by the energy of the driver. Current proton synchrotrons are capable of producing high energy beams, reaching up to multi TeV. Simulations showed that an LHC-type proton bunch (1 TeV,  $10^{11}$  protons), with a  $100 \mu\text{m}$  r.m.s. bunch length, can accelerate an incoming 10 GeV electron bunch to 600 GeV in a single passage through a 450 m long plasma cell with an average gradient  $\geq 1$  GV/m [3]. Proton bunches are thus the most promising drivers of wakefields to accelerate electron and positrons in future TeV lepton colliders.

## 2. The AWAKE Experiment at CERN

The construction of the first proof-of-principle experiment (AWAKE), using high energy and high intensity proton bunches (see beam parameters in Table 1) to generate plasma wakefield acceleration, is under construction at CERN [4, 5].

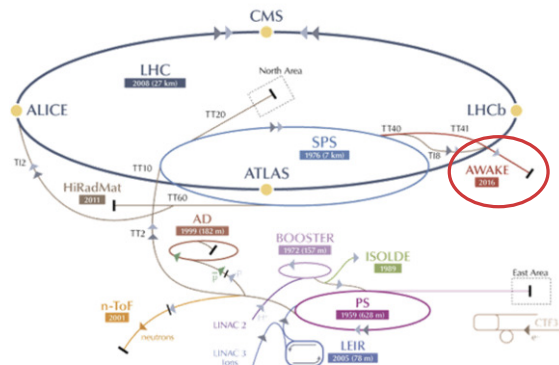


Figure 2: The AWAKE experiment in the CERN Accelerator Complex.

Table 1: Nominal parameters of laser, proton and electron beams.

Laser	
Laser type	Fiber Ti: Sapphire
Power	4 TW
Pulse wavelength	780 nm
Repetition rate	10 Hz
Pulse length	100-120 fs
Pulse energy	>450 mJ
Protons	
Number of bunches	1
Protons per bunch	$3 \cdot 10^{11}$
Repetition rate	0.03 Hz
R.m.s. normalized emittance	3.5 mm mrad
Bunch length	12 cm (0.4 ns)
Momentum	400 GeV/c
Momentum spread	0.35%
Electrons	
Number of bunches	1
Protons per bunch	$1.2 \cdot 10^9$
Repetition rate	10 Hz
R.m.s. normalized emittance	2 mm mrad
Bunch length	1.2 mm (4 ps)
Momentum	10-20 MeV/c
Momentum spread	0.5%

The proton bunch will be produced in the CERN Super Proton Synchrotron (SPS) and extracted towards the TT41 beam line which hosted the CERN Neutrinos to Gran Sasso (CNGS) experiment until 2012 (Fig. 2).

The new experimental apparatus will consist of a 10 m long Rb vapour plasma cell, a  $\sim 20$  MeV electron source and various diagnostics which will be installed at the end of the line. The aim of the experiment is to achieve accelerating gradients of  $\sim 1$  GV/m. In order to reach such a gradient, the plasma density must be  $\sim 10^{15} \text{ cm}^{-3}$  with a density uniformity better than 0.2% [6]. Moreover, the characteristic length scale of the drive bunch must be of the order of the plasma wavelength  $\lambda_p$ , which in this case is  $\sim 1$  mm. The nominal SPS bunch length at top energy (450 GeV/c) is  $\sim 12$  cm and, with the present RF system, can be only reduced by a factor of two (bunch rotation in the longitudinal phase space). However, the theory states that, when a long and narrow (transverse size  $\sigma_{x,y} = 200 \mu\text{m}$ ) bunch of particles travels in a dense plasma, it experiences the so called Self-Modulation Instability (SMI) and is radially modulated in many ultra-short ( $\sim \lambda_p$ ) bunches [7]. A 4 TW laser, co-propagating with the proton bunch, will be used to ionise the Rb gas into plasma and seed the

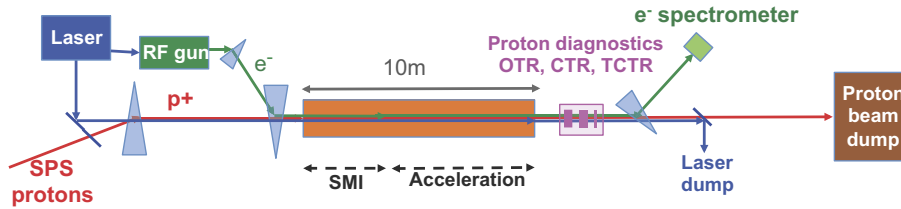


Figure 1: Baseline design of the AWAKE experiment.

SMI in a controlled way.

The measurement program of AWAKE consists of two main phases. “Phase 1” will be dedicated to understand the physics of the proton SMI process in the plasma and benchmark the theoretical models (only laser and proton drive bunch). A witness bunch of electrons (see parameters in Table 1) will be injected in the plasma during “Phase 2” to probe the accelerating wakefields and produce GeV electron bunches.

### 3. Experimental Setup

The baseline layout for the AWAKE experiment is shown in Fig. 1. The RF gun, electron beam line and spectrometer will be installed and operational only for “Phase 2”.

#### 3.1. Phase 1

The final part of the TT41 beam line (last ~80 m) has to be modified to cope with the new experiment requirements. The optics constraints (transverse bunch size  $\sigma_{x,y} = 200 \pm 20 \mu\text{m}$  at the entrance of the plasma cell) can be fulfilled just redistributing and shifting the existing magnets in the line [8]. A horizontal chicane is created to displace the proton bunch from its ideal trajectory and insert a steering mirror which reflects the laser towards the plasma cell.

The successful establishment of the SMI in the plasma strongly depends on the fact that the proton bunch and the laser are synchronised within 100 ps and kept coaxial over the full length of the cell. The latter requires a pointing accuracy of  $100 \mu\text{m}$  and  $15 \mu\text{rad}$  when aligning the proton bunch with respect to the laser at the entrance of the plasma cell [9]. Measurements performed during the CNGS operation showed that an r.m.s. pointing accuracy of  $50 \mu\text{m}$ , averaged over several days, could be obtained at the end of the 800 m long transfer line. Two high resolution ( $50 \mu\text{m}$ ) Beam Position Monitors (BPM) will be installed just upstream of the plasma cell to perform and monitor the relative axial and angular alignment between the two beams.

The plasma source consists of a Rb vapour confined in a 10 m long and 40 mm diameter stainless-steel tube [10]. At the axis of the laser beam the Rb vapour is fully ionised by the laser pulse and the plasma density and uniformity are those of the vapour. The density can be varied between  $10^{14}$  and  $10^{15} \text{ cm}^{-3}$  by adjusting the temperature of the Rb from  $150^\circ \text{C}$  to  $200^\circ \text{C}$ . An oil bath with a heat exchanger are used to keep constant the temperature ( $\Delta T < \pm 0.5 \text{ K}$ ) and, as a consequence, the plasma uniformity within the required 0.2%. First tests were performed on a 3 m long prototype (Fig. 3) and a  $\Delta T < 0.2 \text{ K}$  was measured over 2 m. An interferometry system was used to measure the Rb density [11]. Since

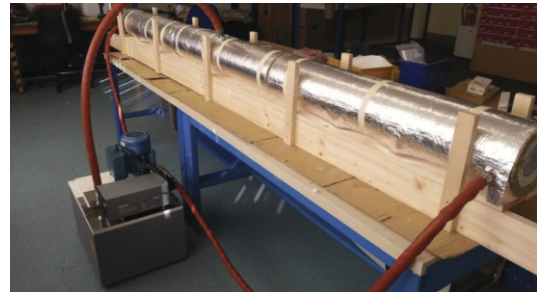


Figure 3: Rb vapour source prototype, courtesy of Grant Instruments Inc.

a window would distort the laser pulse and make it unusable for the ionisation process, fast valves (~15 ms opening time) are installed at both extremities of the vapour source. The repetition rate for the full power laser pulse will be 0.03 Hz (i.e. like the proton bunch); the valves have to be opened every 30 s and survive at least for 43000 cycles (two weeks run) at  $200^\circ \text{C}$ .

Dedicated diagnostics have to be installed downstream of the plasma cell to study the physics of self-modulation and different techniques will be used. An Optical Transition Radiation (OTR) monitor and a ps (up to 200 fs) resolution streak camera will be used to measure the transverse beam size with and without plasma and perform time resolved measurements (modulation period ~4 ps).

Additional detectors will be used for high frequency (273 GHz) and broadband (500 GHz) analysis. In particular, the properties of Coherent Transition Radiation (CTR) as well as the Transverse Coherent Transition Radiation (TCTR) [12] will be measured. The CTR will be used to determine the bunch envelope modulation period. In the TCTR the radially modulated density of the proton bunch should be imprinted to the TCTR amplitude variations. Modules with integrated waveguides and pickup antennas will collect the CTR/TCTR effectively [13].

### 3.2. Phase 2

The RF Photo Injector (PHIN), which is currently in the CLIC test facility (CTF2) at CERN, fulfils the requirements for the electron beam (Table 1) and will be used as electron source for the AWAKE experiment. The annexed diagnostics (see Fig. 4) for beam current (FCT), profile (MS) and phase (BPR) measurements will be also recuperated. Moreover, the klystron and modulator system of CTF3 will be used. The 5 MeV

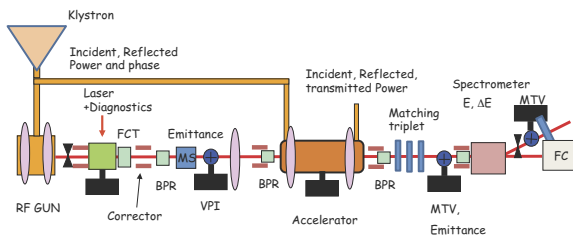


Figure 4: Schematic view of the AWAKE RF gun, accelerating booster and initial part of the electron beam line (from matching triplet).

electron bunch produced at the gun will be accelerated up to 20 MeV by means of a 1 m long booster linac. Three quadrupoles (matching triplet in Fig. 4) will be used to match the optics parameters at the end of the linac with those of the electron beam line and also to perform quadrupole scans for emittance measurements. For this purpose, a profile monitor (MTV) will be located right downstream of the triplet. A vertical dipole will be used to bend the electron beam towards the newly built tunnel (7 m long and 2.5 m wide) which connects the RF gun with the existing proton tunnel (Fig. 5). This magnet, together with another MTV installed in the line downstream of the dipole, will also be used as spectrometer to measure the energy of the electron beam after the linac. When the magnet is off, the beam goes straight into a dump equipped with a Faraday Cup for current measurements. The electron bunch is transported towards the plasma cell by means of a

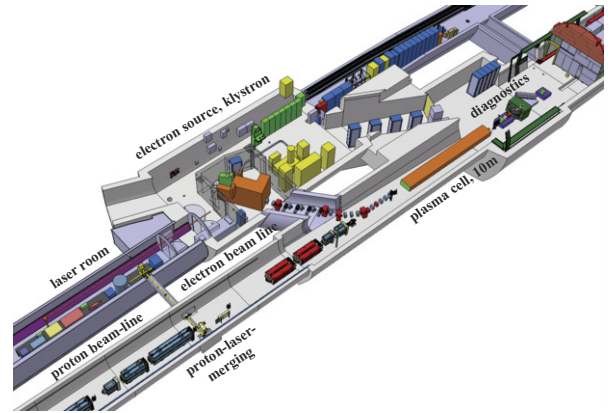


Figure 5: Integration of the AWAKE experiment in the CNGS experimental area at CERN.

13.5 m long transfer line. The laser, proton and electron beams are on the same axis (on-axis injection) and share the same beam pipe over the last ~4 m before the plasma cell. A common diagnostics has to be envisaged for their relative alignment (OTRs and BPMs).

A CERN MBPS dipole (1 m long, with a horizontal and vertical aperture of 300 mm and 140 mm respectively and a magnetic field of up to 1.84 T) will be used as spectrometer to measure the peak energy and energy spread of the captured electrons downstream of the plasma cell. A scintillator screen and an intensified CCD camera will be used to measure the spectrum of the dispersed electrons. This system will allow performing measurements in a range between 10 MeV and 5 GeV.

## 4. Expected Results

Simulations of the electron injection into the proton driven wakefields and evolution over the full 10 m long plasma cell were performed with LCODE [14]. These studies showed that the electrons are trapped from the beginning by the seed perturbation and move with the wave while the bunch self-modulates. Because of the superluminal behaviour of the phase velocity of the plasma wake after the SMI saturation, the trapped electrons, which were previously oscillating near the minimum of accelerating/decelerating electric field  $E_z$ , end up in the accelerating phase. The expected electron capture efficiency for the parameters shown in Table 1 is 10–15%; high sensitivity diagnostics is therefore needed for the electron spectrometer. According to simulations, the captured electrons are accelerated up to an average energy of 1.3 GeV. A large energy ( $\pm 0.4$  GeV) and angular ( $\pm 4$  mrad) spread are calculated [15], as shown in Fig. 6.



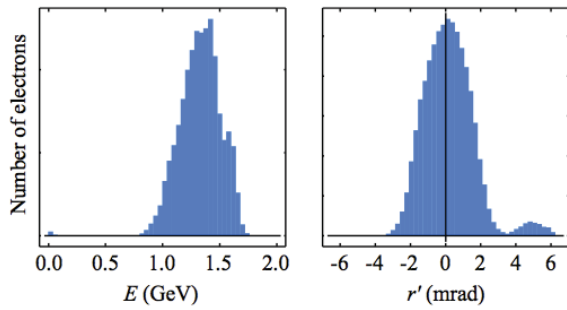


Figure 6: Calculated energy and angular distribution of the captured electrons at the exit of the plasma cell.

## 5. Present Status and Future Steps

The first AWAKE collaboration meeting took place in June 2012 in Lisbon. Feasibility and integration studies (Fig. 5) followed to define the best location for the experimental facility, required modifications, needed civil engineering works, services, equipment, budget, manpower, etc.. The AWAKE Design report was completed and submitted to the CERN management in February 2013 and the project was fully approved in August 2013.

	2013	2014	2015	2016	2017	2018
Proton beam-line			Installation	Commissioning	data taking	
Experimental area		Study, Design, Procurement, Component preparation	Modification, Civil Engineering and installation		data taking	
Electron source and beam-line		Studies, design	Fabrication	Installation	Commissioning	data taking

Figure 7: Planning of the AWAKE activities until LS2.

Detailed design studies, procurement and preparation of the different components are ongoing and civil engineering works for the electron and laser tunnel are planned to start in July 2014. A tight and challenging schedule (Fig. 7) is foreseen for this project in order to be able to collect enough data before the next long shutdown (LS2) of the CERN accelerator complex (mid 2018).

The main milestones of the AWAKE commissioning are:

- Phase 1: first proton and laser beam up to the plasma cell by mid 2016
- Phase 2: first electron beam up to the plasma cell by end 2017.

An upgrade program (“Phase 3”, after LS2) is already being studied. In this scenario, one plasma cell is used

for the proton bunch self-modulation and is followed by a second plasma stage (Helicon or Argon plasma discharge cell) where the electrons are injected and accelerated up to the multi-GeV scale (Fig. 8). Ultra-short electron bunches ( $\sim 300$  fs) have to be used for “Phase 3” and a bunch compression system has to be integrated in the lattice of the electron beam line. Alternatively, injection of a laser wakefield-produced electron bunch is also considered [16]. Simulations predict an increase in the

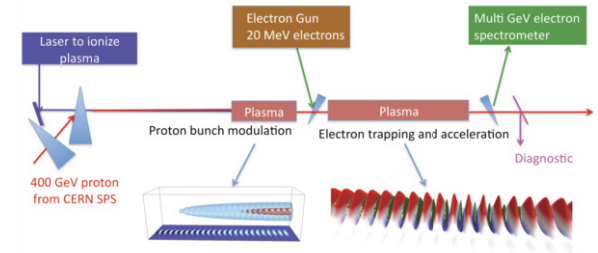


Figure 8: Schematic layout of the AWAKE experimental setup for “Phase 3” operation.

electron capture efficiency to almost 100%, an improved beam quality with a narrower energy spread and transverse emittance and a larger energy transfer efficiency. This would be a fundamental step towards the application of plasma technology to accelerator physics since high brightness beams are an indispensable requirement for lepton linear colliders.

## 6. Conclusions

Proton bunches are the most promising drivers for wakefields to accelerate electrons to the TeV energy scale and build compact lepton linear colliders. AWAKE is the first proton-driven R&D experiment and is at present being built at CERN. It will use a 400 GeV SPS proton bunch as drive bunch, a 4 TW laser to ionise the Rb vapour into plasma and seed the SMI in a controlled way and a 10-20 MeV electron bunch as witness bunch. “Phase 1” (starting in 2016) will allow to study the physics of self modulation as a function of different plasma and proton beam parameters as well as benchmark the theoretical models. The longitudinally accelerating fields will be probed during “Phase 2” (2017-2018) by injecting an external bunch of electrons coaxial with the laser and proton beams. Studies on injection dynamics and production of multi-GeV electron bunches will follow and an upgrade program is being prepared for operation after LS2 (“Phase 3” in 2022). The final scope of this project is to prove that acceleration of electrons up to 100 GeV in 100 m is possible

and “good” quality beams can be produced in view of the application to TeV lepton colliders.

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